REPORT No. 805

AN ANALYSIS OF LIFE EXPECTANCY OF AIRPLANE WINGS IN NORMAL CRUISING FLIGHT

By Abbott A. Putnam

SUMMARY

In order to provide a basis for judging the relative importance of wing failure by fatigue and by single intense gusts, an analysis of wing life for normal cruising flight was made based on data on the frequency of atmospheric gusts. The independent variables considered in the analysis included stress-concentration factor, stress-load relation, wing loading, design and cruising speeds, design gust velocity, and airplane size. Several methods for estimating fatigue life from gust frequencies are discussed. The procedure selected for the analysis is believed to be simple and reasonably accurate, though slightly conservative.

The results of the analysis indicate that, in general, the fatigue life and single-gust life of an airplane wing are of about equal importance for conventional designs and normal operating conditions. The fatigue life appears to be influenced mainly by the detail design and construction and not greatly by normal changes in operating speed or by moderate changes in the design gust velocity. Single-gust life, however, is not appreciably affected by the detail design and construction but is markedly affected by operating speed and by changes in design gust velocity. The trends in design toward higher wing loading, reduced load factor, larger size, and increased speed appear to have a small effect on both fatigue life and single-gust life.

INTRODUCTION

Considerable interest has recently developed in this country concerning the fatigue life expectancy of the primary structure of an airplane. The trends in airplane design toward higher speed, higher wing loading, and larger size have been cited as indications that fatigue troubles and reduced life are becoming of increasing importance. Available literature does not show very clearly, however, whether fatigue life is important. Authentic cases of fatigue failure of the primary structure have not been cited. Furthermore, no evidence has been presented for assuming that design trends shorten fatigue life. The obscurity of this subject is partly the result of the absence of statistical data on the repeated loads or stresses to which airplane structures may be subjected in service operations and the consequent absence of analytical treatments of the problem.

In order to estimate the relative importance of fatigue in the primary structure, an analysis is made herein of the effects of a number of variables on the fatigue life of airplane wing structures subjected to the numerous gusts encountered in normal transport flight operations. For this purpose, the statistical gust data of reference 1 have been utilized. The values of fatigue life thus obtained are compared with the life expectancy based on the probability of encountering single gusts of excessive magnitude.

In most of the cases analyzed, it is assumed that the wing is designed to withstand a static load corresponding to the load imposed by a gust having a velocity of 30 feet per second at design level-flight speed. For this condition the effects of stress-concentration factor, fatigue properties of the structural material, design speed, design wing loading, and stress-load relation were determined. The effects of variation of the design load condition are also determined and the effect of airplane size is considered.

METHOD OF ANALYSIS

SINGLE-GUST LIFE

As pointed out in reference 1, "Life expectancy is governed not only by fatigue but also by the probability of occurrence of single quasi-static loads of such high magnitude as might endanger the structure directly." The probable life, as governed by the action of a single excessive gust, may be termed the "single-gust life" and is taken herein as the number of miles required, on the average, to encounter a gust sufficiently strong to induce a stress equal to or exceeding the yield-point stress. Since increased airspeed reduces the gust intensity required to develop any given stress, for a given airplane the frequency of occurrence of the critical stress will increase with increasing airspeed and hence the single-gust life will depend upon the actual operating speed.

FATIGUE LIFE

The problem of determining the fatigue life of an aircraft structural member subjected to the randomly varying loads caused by atmospheric turbulence may be discussed in three phases: the interpretation of available gust-frequency data for fatigue studies, the determination of the fatigue life of a material under random stress variations, and the consideration of the effect of stress concentrations in structural members. As various methods of solving each of these three components of the problem are available, several methods are discussed briefly and a procedure is chosen as a basis for this analysis. Although the procedure selected gives reasonable values of life expectancy, the present status of knowledge concerning every part of this problem and the problem as a whole is such that reliance should be placed only on the trends and general implications of the results, not on the absolute magnitudes of fatigue life.

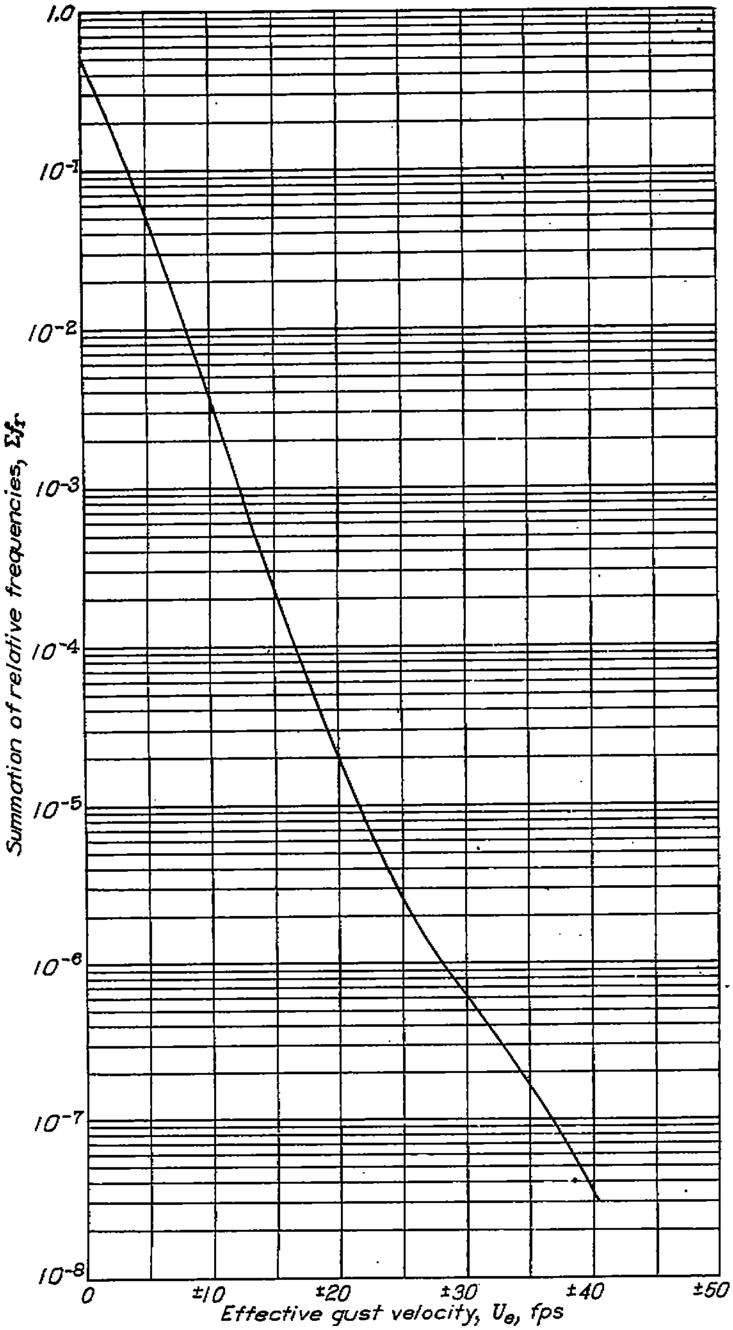

FIGURE 1.—Unit summation curve of relative gust frequencies. (Curve A of fig. 7, reference 1.)

Interpretation of gust data.—The determination of the stress associated with a given effective gust velocity for the usual assumptions of static loading and uniform distribution of gust velocity along the span is a well-known process. In spite of their limitations, these assumptions appear to give reasonably accurate results. (See reference 1.) In the present analysis the usual assumptions are therefore retained and the gust intensities are converted to stress intensities by using the simple gust formula (equation (1) of reference 1).

Fatigue analysis requires the determination of the stresses associated not with a single gust but with many gusts of various magnitudes. Data on the frequency of occurrence of gusts of various magnitudes are presented in reference 1. As shown there, the frequency distribution may be represented by the summation curve of the relative-frequency distribution; such a summation curve is reproduced as figure 1 (curve A of fig. 7, reference 1). This curve, together with the data on total number of gusts per mile of operation given in reference 1, provides a basis for the determination of the number of stress cycles per mile of operation.

A simple and common way of interpreting gust-frequency data for fatigue studies is to group the gusts in pairs of equal magnitudes having opposite signs for conversion to stress cycles about a constant mean stress corresponding to the $1g$ load on the airplane structure. Unpublished results indicate that, actually, only about two-thirds of the gusts are grouped in this manner and the other third are not. A more nearly correct representation of the other one-third of the data would be effected if the number of cycles for this third were doubled and the range of stress reduced to one-half of the range in the simpler representation. The more refined interpretation would also change the mean stress from the values corresponding to $1g$ to a set of values dependent upon the stress amplitudes. Examination of fatigue data indicates that the net effect of the changes introduced by the closer approximation of the gust data is to increase the estimated fatigue life, primarily because of the great effect of the reduction of stress range. The more common interpretation, because it is somewhat more conservative as well as simpler, has been chosen as a basis for the present analysis.

Application of fatigue data for materials.—For practical reasons, fatigue tests of materials are usually made in such a way that the fatigue life for a given mean stress is found in terms of the number of stress cycles required to cause failure with constant amplitude of the stress cycle. The results of such tests indicate, as is well known, that the number of cycles required to cause failure decreases as the stress amplitude or maximum stress increases. The data are usually represented in the form of S–N curves, an example of which is shown in figure 2. Even in the case of simple specimens of material, the scatter of the data is so large that the determination of the number of cycles required to cause failure is accurate only within a factor of 2 or 3 and even greater factors are not at all uncommon.

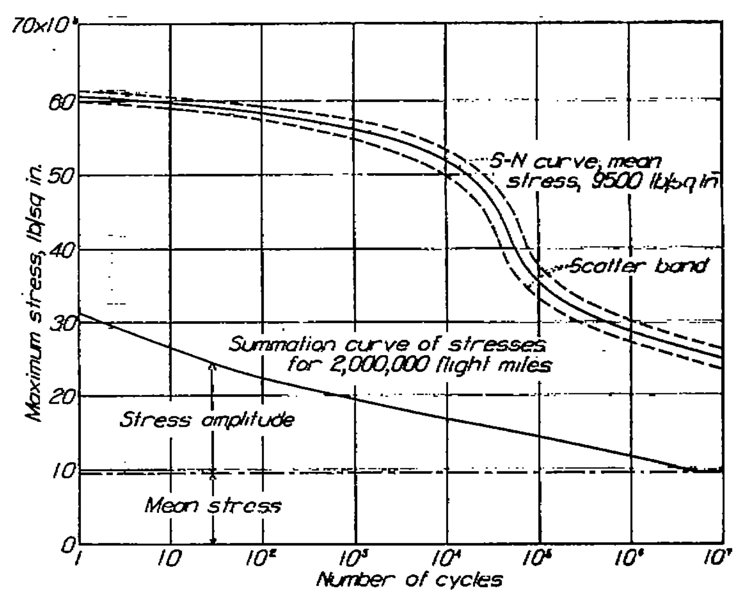

FIGURE 2.—Sample data for computation of fatigue life.

Fatigue tests in which the actual nature of stress fluctuations is precisely represented have not been made, although a few tests have been made in which stress amplitude has been changed on single specimens. Although some general tendencies have been disclosed by these tests, the data are inadequate to provide a basis for the prediction of fatigue life under the action of random stress fluctuations. Since there is no known way of adding the effects of random stress fluctuations correctly, some leveling or averaging method of adding these effects must be used.

One method, which might be called the linear method, is to assume a straight-line damaging effect of the cycles at any stress level. The number of applied cycles at any level is divided by the number of cycles required to cause failure at that level to obtain the fractional damage done. The cumulative effect or damage caused by all stresses is thus the sum of the fractional damages at each level and, if the sum exceeds 1.0, failure is assumed to have occurred. The basic concept of this method seems reasonable, but a difficulty arises in making the proper choice of stress interval. The use of too large an interval will give erroneous results whereas too small an interval will result in an excessive amount of computation and a false concept of accuracy. The optimum stress interval is therefore a matter of personal judgment and experience. Another deficiency in the linear method is that it does not account for the effect of stresses below the endurance limit. The effects of these lower stresses may be beneficial and can be taken into account by means of a modification suggested by Langer (reference 2), in which an average fractional damage or repair is assigned to each cycle at each level. This procedure is cumbersome and requires far more experimental data than are now available.

Another method of predicting the fatigue life of a material, which might be called the intersect method, involves the assumption (reference 3) that, for any total number of cycles or any duration of operation, the material is safe if the summation curve of the applied stress cycles remains below the corresponding S–N curve of the material (fig. 2). In comparing the summation and S–N curves, it is found convenient to hold the mean stress constant. The fatigue life is found when the stress-cycle summation curve, which shifts to the right with increasing number of miles flown, contacts the corresponding S–N curve of the material. The intersect method involves the implication either that the damage line is very close to the S–N curve for the material considered or that, in the region of contact, the net beneficial effect of the stress cycles below any level compensates for the damaging effect of the higher stress cycles to such an extent that all the higher stress cycles can be considered to occur at that level. The few applicable test results (reference 4) indicate that this assumption is reasonable.

The linear method gives somewhat shorter life (within the limits of scatter of fatigue-test results) than the intersect method when applied to the stress summation curve derived from gust-frequency data. Applicable fatigue-test results are too few, however, to permit conclusions concerning the relative accuracy of the two methods. Since the intersect method has the advantage of simplicity, this method is utilized in the analysis.

Stress-concentration factors.—So long as the maximum stresses in tension and compression are below the elastic limit, any given stress-concentration factor may be applied in the customary manner (reference 5). The determination of the proper stress-concentration factor, however, presents some difficulty. When stresses above the elastic limit are considered, furthermore, the unloading effect of plastic action in the region of stress concentration reduces the maximum stress below that given by the stress-concentration factor.

If the average mean stress in cyclic loading is not zero, the effect of the plastic action is to reduce the mean stress at the point of stress concentration. The hypothesis used in this report is that the first cycle which causes plastic action results in a lowering of the mean stress in the region of stress concentration but that the entire stress-concentration factor is still effective with regard to the range of a cycle in this region. As an example, if a stress-concentration factor of 3 is present and the average mean stress in the member is A, the value of the stress at the point of stress concentration is $3A$. If the average stress is now increased by B, the stress at the point becomes $3(A+B)$ under elastic conditions. If the amount $3B$ is sufficient to cause plastic action, however, the most highly stressed portion will unload to a less highly stressed portion and the maximum stress will be $3(A+B)-\Delta$, where Δ is the amount of unloading. The material at that point will behave elastically when the average-stress increment B is removed; and when the stress at the point of maximum stress concentration decreases by the corresponding amount $3B$, the mean stress at the point becomes $3A-\Delta$. Subsequently, as long as no average-stress increment exceeding B is imparted to the member, the stress cycles in the region of maximum stress concentration will be acting about the lower mean stress $3A-\Delta$.

One way of determining the amount of lowering of the mean stress due to plastic action in the region of stress concentration would be to make use of the stress-strain curve of the material and a relaxation method of computation (references 6 and 7). Such a process would be tedious and the result still in doubt. A simple method was therefore sought for calculating the stresses in the plastic region. It is well known that, for moderate stress concentrations in ductile materials, the stress approaches uniformity at the ultimate strength. This fact led to Hartmann's assumption (reference 8) that the stress-concentration factor decreases linearly from the maximum value at three-fourths the yield strength to a value of 1 at the ultimate strength. This assumption may be used in conjunction with the discussion just given on cyclic loading in the plastic region to predict fatigue life, provided the initial stress-concentration factor can be determined.

When plastic action is taken into account, no single fatigue life can be determined, as can be seen from the following considerations. The limiting stress range of a material for any given number of cycles ordinarily decreases slightly with increasing mean stress at the lower mean stresses; however, the rate of decrease may become quite large at higher mean stresses (reference 9). Thus, since the material at the point of stress concentration operates at a relatively high mean stress, provided an initial cycle has not caused plastic action, the fatigue life is slightly low as compared with the life corresponding to the lower mean stress. If the initial cycle has caused plastic action in the material, with resultant reduction of mean stress for subsequent cycles of lower amplitude, the fatigue life is somewhat increased in accordance with the reduction in mean stress. In summation, the following assumptions were used concerning plastic action: that plastic flow takes place as expressed by Hartmann's relation, that no plastic flow takes place subsequent to the first cycle, and that any range of stress remains constant at the full value of the stress-concentration factor times the average-stress range.

Since the fatigue life is affected by the order in which the larger stresses occur, the fatigue life may be plotted as a function of the first stress encountered, as shown in figure 3. It is

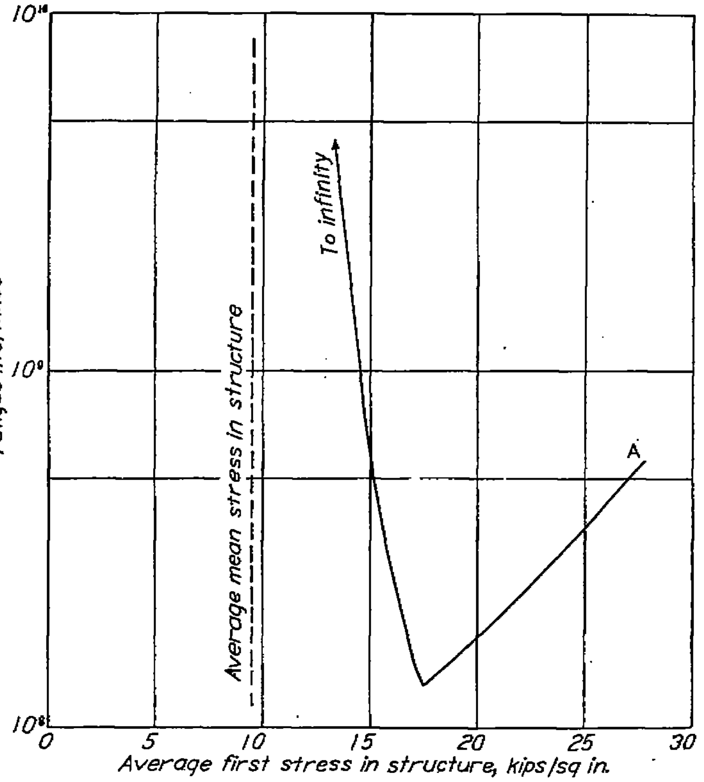

FIGURE 3.—Variation of fatigue life with average first stress in structure for a stress-concentration factor of 2.4. Material, 17S–T aluminum alloy; wing loading, 24.3 pounds per square foot; cruising speed, 170 miles per hour.

assumed for this curve that no stress greater than the first is experienced. The life obtained when the first stress encountered is high enough to make the mean stress at the point of maximum stress concentration become zero will be referred to as the "maximum life" (point A in fig. 3). From the maximum life, the fatigue life decreases with decreasing first stress because of increasing mean stress in the region of stress concentration. A reversal in the curve occurs, however, because of the decreasing stress amplitudes; and the fatigue life approaches infinity as the stress decreases. The life at the point of reversal is considered the minimum life. Actually, if a low first stress is subsequently exceeded, the potential life is increased from that given by the first mean-stress level toward that of the new mean-stress level. It may be seen that, for normal gust distribution, the fatigue life must fall between these two extremes.

CONDITIONS OF ANALYSIS

Although the analysis is restricted to the wing and takes account of only the stresses induced by atmospheric gusts, a considerable number of variables influence both the fatigue life and the single-gust life. In order to keep the analysis as simple as possible and at the same time to bring out the important points, those variables that affect the fatigue life and the single-gust life in the same ratio are held constant. For example, the size and the geometrical configuration of the airplane have been found to affect the two lives equally; the analysis is therefore presented for only one size and one configuration, although the influence of these variables on the lives will be evident later. The analysis is mostly for only one structural material because, although the effect of change of material is not negligible, the influence of other variables is relatively unaffected by the material chosen. A check is given, however, for a second material. Although gust frequency is actually variable (reference 1), it is assumed to be constant because the influence of changes in gust frequency can be easily evaluated without specific treatment in the analysis. Variables specifically treated include structural detail—such as stress concentration and stress-load relation—design speed, design wing loading, and basic design criterions.

CONSTANT FACTORS

Airplane size and configuration.—The airplane size and configuration selected for the analysis represent a hypothetical airplane having the wing dimensions of the Douglas DC–3. The important factors governed by this choice are the mean wing chord, 10.4 feet, and the slope of the wing lift curve, 4.8.

Material of construction.—It was found desirable to have the S–N curves of the selected material range from static load conditions to a great number of cycles. Since the fatigue characteristics of the common aluminum alloy 17S–T in the region of high stresses and small numbers of cycles had been investigated in reference 10 and since additional fatigue data of the usual type were available in reference 11, 17S–T was used as the basic material. Another common aluminum alloy, 24S–T, was investigated sufficiently to determine the effect of changing to this material.

Gust frequency.—The analysis is made for the unit summation curve of relative gust frequencies (fig. 1). This summation curve is the upper limit of the unit summation curves of gusts from various sources and, consequently, leads to conservative estimates of both fatigue life and single-gust life. The absolute gust frequency used in the analysis, $50/\bar{c}$ gusts per mile, was based on the data given in reference 1 and is about average for normal transport operations ($\bar{c}$ denotes mean wing chord in ft).

VARIABLE FACTORS

Structural details.—Since stress concentrations in such forms as holes, fillets, grooves, bends, and surface blemishes occur in all structures, the variation of fatigue life with stress-concentration factors from 1 to 6 was investigated. Usual stress-concentration factors for well-designed and well-fabricated structures are within this range although the higher values are not precluded. A typical value in a structure ideal except for stress concentrations is 2.4, and in some examples this value is used as a constant while other quantities are varied.

"Nonlinear" loading occurs in structures typical of normal construction when one portion of a structure is overloaded because another portion fails to carry its design share of the load as a result of improper design or fabrication. As the elastic limit is exceeded, the overloaded portion of the structure may be relieved more and more, with the result that at the higher loads the loading tends to become uniform. Consequently, although the fatigue life is greatly affected, the static properties and single-gust life are not materially altered. In order to determine the magnitude of the effect on fatigue life, a comparison was made between the ideal structure and one in which such overloading was present. In the structure selected, the overload factor was 4/3 up to the elastic limit, after which the factor was reduced linearly to a value of unity at the yield point.

Operating conditions.—Although operating conditions determine the ratio of flight path in rough air to total flight path and thereby affect the gust frequency per mile of operation, the gust frequency per mile is held constant for reasons previously given. The actual operating speed also has an important effect on both the fatigue life and the single-gust life; a variation of this speed in roughest air is considered in the analysis.

Whereas the airplane is assumed to be designed statically to yield with application of a 30-foot-per-second gust at design level-flight speed, the airplane is assumed to operate normally at a cruising speed of 0.8 of the design speed. Inasmuch as good operational practice requires a reduction in speed below the normal cruising value when the air is extremely rough, the influence of a reduction in speed from 0.8 to 0.6 of the design speed during stretches of extremely rough air was determined.

Design conditions.—It was assumed, in general, that the airplane was designed to yield with application of an effective gust velocity of 30 feet per second at design level-flight speed and that the stress was zero at zero load factor. The effect of reducing the design gust velocity to 25 feet per second was evaluated for one condition of design speed and wing loading. For a design for an effective gust velocity of 30 feet per second, the effects of variation in wing loading from 10 to 50 pounds per square foot and variation in design level-flight speed from 125 to 425 miles per hour were evaluated.

RESULTS AND DISCUSSION

EFFECT OF STRUCTURAL PARAMETERS

Stress-concentration factor.—The effect of increasing stress-concentration factor on the fatigue life of a wing structure ideal except for stress concentrations is shown in figure 4. The results are given for two materials, 17S–T and 24S–T aluminum alloy, and indicate both the maximum and minimum lives as determined by the most favorable and the least favorable sequence of gusts. As is readily apparent, the fatigue life decreases rapidly with increasing stress-concentration factor, so that fairly short life is possible with moderately high values of the factor.

The comparison between 17S–T and 24S–T aluminum alloys shown in figure 4 is not intended as an analysis of the effects of different materials on fatigue strength but was made simply as a check to insure that the choice of one in preference to the other would not seriously alter the implications of the general analysis, which has been carried out only for 17S–T. The difference in fatigue lives for the two materials is not large. This result cannot, of course, be construed to mean that choice of material generally has no influence on the fatigue life. The similarity in the results for 17S–T and 24S–T materials might have been expected, because the ratio of the fatigue strength to ultimate strength

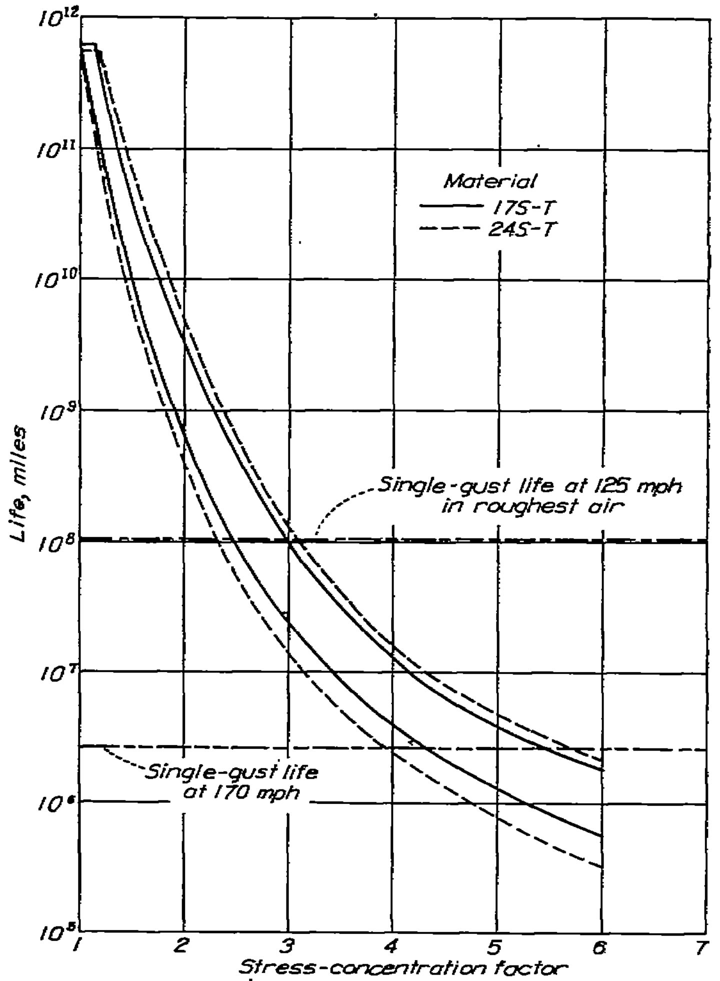

FIGURE 4.—Effect of stress-concentration factor and material of construction on fatigue life. Assumed wing structure designed to yield with gust velocity of 30 feet per second at 213 miles per hour; airplane assumed to operate at cruising speed of 170 miles per hour.

in both materials is about the same. In other words, the higher strength of 24S–T, which causes increased stress amplitudes for the assumed design conditions, is about offset by an improvement in the fatigue-strength qualities of the material. In the case of certain high-strength alloys, the fatigue life may sometimes be adversely affected for two reasons: a reduction in the ratio of fatigue strength to ultimate strength and an increase in notch sensitivity.

The stress-concentration factor does not affect the single-gust life, which is shown in figure 4 for the normal cruising speed of 170 miles per hour and for a speed reduction to 125 miles per hour in the roughest air. It is well known that moderate stress-concentration factors do not appreciably affect static strength of ductile materials because of the localized nature of the high stress and because the plastic flow of material in the region of stress concentration causes more uniform distribution of stress at the higher loads. Since the single-gust loading condition is a "static" phenomenon, as contrasted with a fatigue phenomenon, the single-gust life remains constant over a wide range of stress-concentration factors.

Nonlinear stress-load relation.—The effect of a typical structural imperfection resulting from design or fabrication is shown in figure 5, which also shows the results given in figure 4 for 17S–T material. The nature of the imperfection has been described in a previous section. The considerable shortening of fatigue life resulting from this imperfection is clearly evident and corresponds approximately to the reduction caused by multiplying the stress-concentration factor by 4/3.

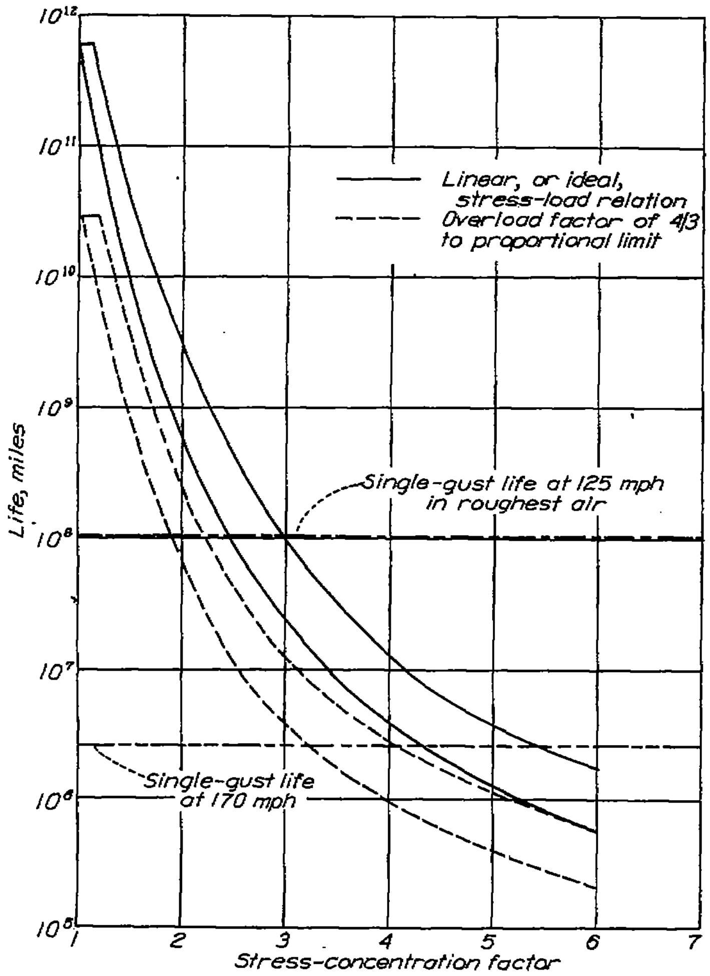

FIGURE 5.—Effect on fatigue life of a nonlinear stress-load relation. Assumed wing structure designed to yield with gust velocity of 30 feet per second at 213 miles per hour; airplane assumed to operate at cruising speed of 170 miles per hour. (Material, 17S–T aluminum alloy).

Single-gust life is unaffected by the structural imperfection because the yield point was assumed to have been reached with all the material active. With some types of structural imperfection, this assumption would not apply and the single-gust life, as defined on the basis of yield-point stress, would be slightly affected. In no ordinary case, however, would the ultimate static strength of the structure be appreciably affected by the type of structural imperfection under consideration; hence the single-gust life may be considered to be unaffected.

EFFECT OF OPERATING CONDITIONS

Reduction of operating speed in roughest air.—Both figures 4 and 5 show that the single-gust life is materially affected by the operating speed. In the case assumed, the single-gust life corresponding to operation at a cruising speed of 170 miles per hour is 2.6×10^6 miles, whereas the life corresponding to reduction of operating speed to 125 miles per hour when the roughest air is encountered is 1.04×10^8 miles. It should be noted that the reduced speed need be assumed to apply not to the entire operating life but only to the relatively small part during which the roughest air is encountered.

The reduction of operating speed in the roughest air has a negligible effect on the fatigue life, because only the stresses resulting from the relatively few larger gusts and from a small number of the smaller gusts have been diminished. Diminishing the infrequent large stresses on the summation curve (fig. 2) does not influence the number of cycles of the smaller stresses required to cause contact of the summation and S–N curves. When the large stresses are diminished by a reduction of speed, some of the smaller stresses resulting from the less severe gusts encountered during the operations in the roughest air will also be diminished. The number of less intense gusts encountered during the short stretches of the roughest air, however, is small compared with the total number of the less intense gusts and the fatigue life is only very slightly increased by the reduction in operating speed. This effect has been neglected in the analysis.

Variations in gust frequency.—As pointed out in reference 1, the total frequency of significant gusts may be defined in terms of the path ratio, which is the ratio of the flight path in rough air to the total path of operations. The value of $50/\bar{c}$ gusts per mile chosen for the present analysis corresponds to a path ratio of approximately 0.1, which is the mean value for a number of different operating conditions. The data of reference 1 indicate that the path ratio may vary between values of 0.006 and 0.24 according to the operating conditions. The fatigue lives shown in the results presented here may therefore be multiplied by appropriate factors to determine the fatigue lives corresponding to operating conditions other than average. Similarly, the path ratio has a direct effect on the single-gust life.

EFFECT OF TRENDS IN DESIGN AND REDUCTION OF DESIGN GUST VELOCITY

Wing loading.—Because wing loading has shown a marked tendency to increase with the development of new designs, there has been some fear that the corresponding increase in the mean-stress level would result in shortening the fatigue life. If the design load factor is based on an effective gust velocity of 30 feet per second, however, there is an offsetting influence in that the stress amplitudes are reduced for a given set of gust intensities.

The net effect on fatigue life and single-gust life of change in wing loading when the design is based on an effective gust velocity of 30 feet per second is shown in figure 6. The maximum and minimum fatigue lives are shown for two values of the stress-concentration factor, 2.4 and 6.0; the single-gust lives are shown for comparison. It is evident that the net

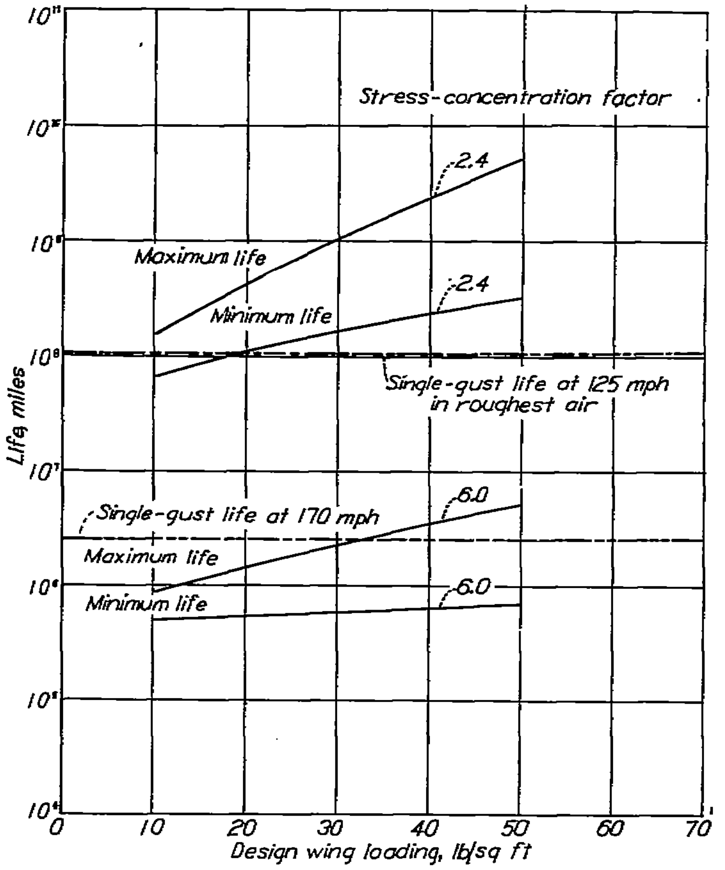

FIGURE 6.—Effect of design wing loading on fatigue life with two stress-concentration factors Assumed wing structure designed to yield with gust velocity of 30 feet per second at 213 miles per hour at each value of design wing loading; airplane assumed to operate at cruising speed of 170 miles per hour. (Material, 17S-T aluminum alloy.)

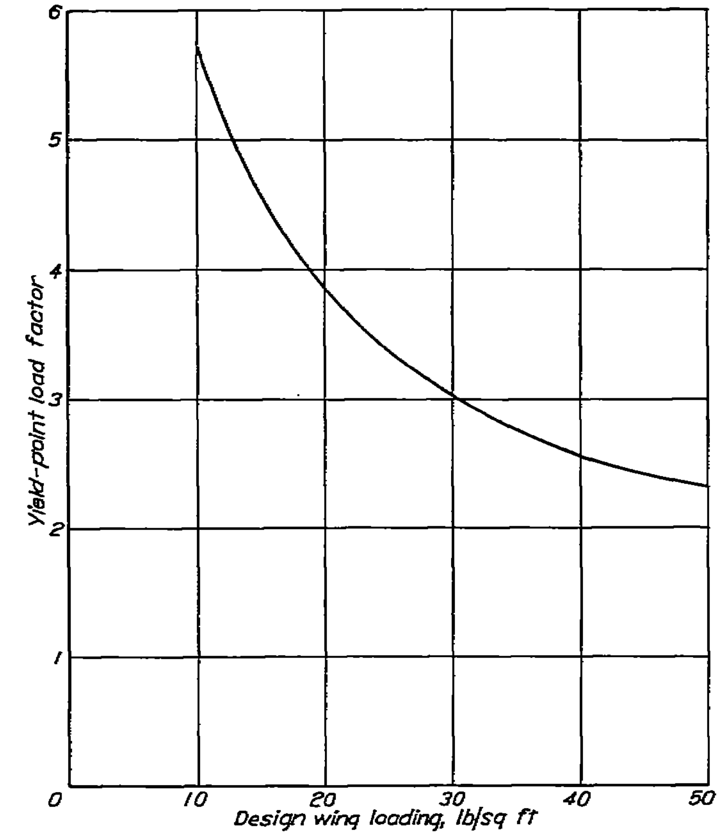

FIGURE 7.—Variation of yield-point load factor with design wing loading. Assumed wing structure designed to yield with gust velocity of 30 feet per second at 213 miles per hour.

effect on the fatigue life of increasing the design wing loading is favorable, although the effect is only moderate for the higher values of stress-concentration factor. This result indicates that the favorable effect of reduction in stress amplitudes has more than offset the deleterious effect of the increase in mean stress. Single-gust life remains the same at all values of the wing loading.

Another trend in design, which has been cited as causing a reduction of fatigue life, is the trend toward lower design load factors. Although the effect of reduction of load factor has not been evaluated with other factors remaining constant, it may be pointed out that increasing the wing loading lowers the load factor when the design is based on the gust criterion. Consequently, lengthening of fatigue life with increasing wing loading actually exists notwithstanding rather marked reduction in the load factor. Figure 7 shows the yield-point load factors corresponding to the wing loadings of figure 6. The load factor decreases from about 5.7 to 2.3 as the wing loading increases from 10 to 50 pounds per square foot. Although the reduction in load factor occurs at the same time as an increase in the wing loading, it should be borne in mind that trends in various features of design are concurrent rather than separate; hence the result shown in figure 6 is probably a fairly accurate indication of the effect of design wing loading on fatigue life.

Speed.—The effect on fatigue life of increasing the design speed is shown in figure 8. The single-gust life is not appreciably affected by increasing design speed, because the design

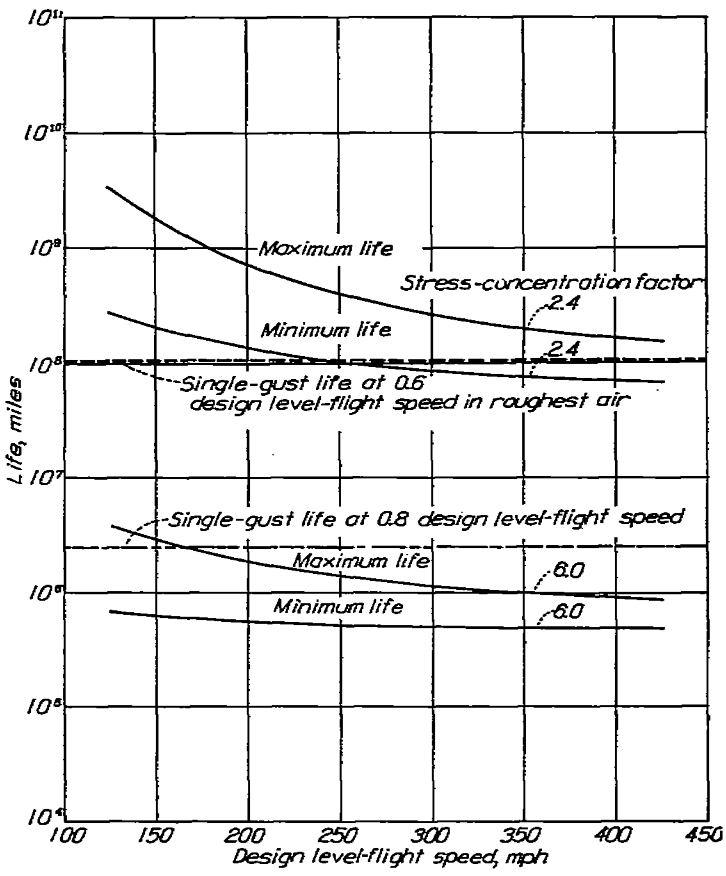

FIGURE 8.—Effect of design airspeed on fatigue life with two stress-concentration factors. Assumed wing structure designed to yield with gust velocity of 30 feet per second at each value of design level-flight speed; airplane assumed to operate at 0.8 design level-flight speed. (Material, 17S-T aluminum alloy.)

is assumed to be based on a gust criterion. Although fatigue life is evidently adversely affected by increasing speed, the effect is only moderate. The effect of speed approximately offsets the favorable effect produced by increasing the wing loading, so that, if the wing loading and speed are increased concurrently, not much change in fatigue life occurs.

The fatigue life is given in terms of operating miles, the important economic factor, rather than in terms of hours of operation. If expressed in hours, the fatigue life would appear to be more adversely affected by increasing speed.

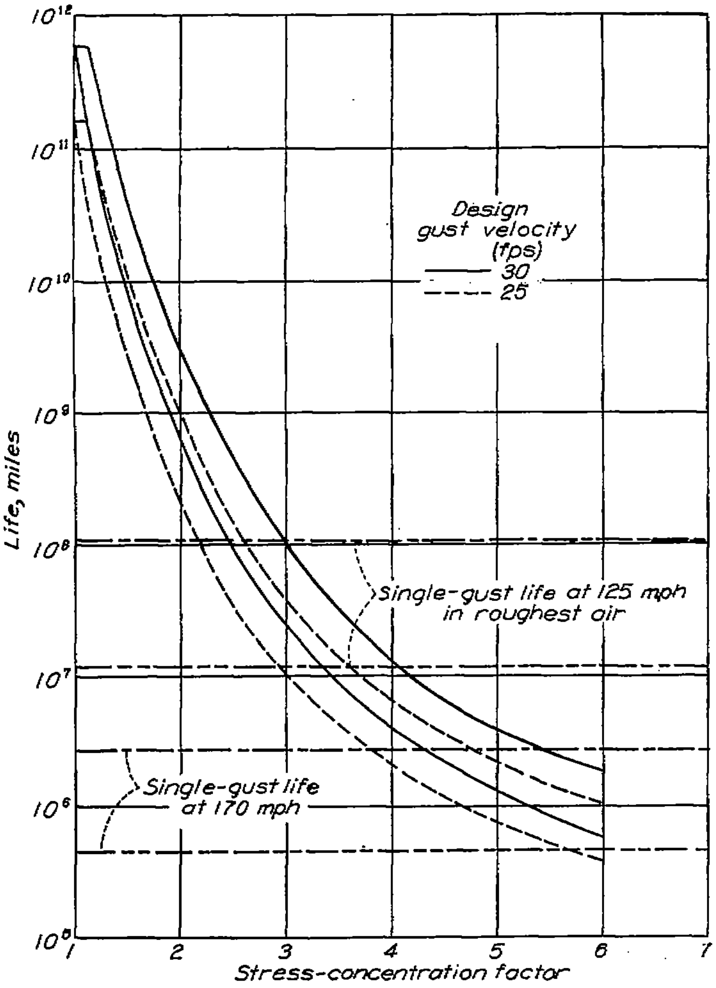

FIGURE 9.—Effect of reduction of design gust velocity on fatigue life with varying stress-concentration factor. Assumed wing structure designed to yield with design gust velocity at 213 miles per hour; airplane assumed to operate at cruising speed of 170 miles per hour. (Material, 17S-T aluminum alloy.)

Airplane size.—Data showing that the total frequency of significant gusts is inversely proportional to the wing chord are given in reference 1. In accordance with these data, both the single-gust life and the fatigue life may be expected to increase linearly with increasing wing chord.

Reduction of design gust velocity.—The effect of a reduction in the design gust velocity from 30 feet per second to 25 feet per second is shown in figure 9. It is evident that the fatigue life is not greatly reduced by this change but that the single-gust life is reduced to about one-eighth of its original value.

EFFECT OF OTHER FACTORS

The results of the analysis, although somewhat limited in scope and possibly oversimplified, provide a basis for assessing the relative importance on airplane life of fatigue and single-gust failures. These results may be better appraised by qualitative consideration of some influences that have been neglected in the analysis.

In flight through turbulent air some dynamic overstress may be present, especially near the wing tips. Stress increments due to such dynamic effects may be about 10 percent of the stress increments resulting from static-load application. Such incremental stresses may be introduced into the fatigue analysis by changing the load-stress relation in obtaining the stress summation curve. General conclusions, however, may be drawn by considering figure 9. The change in design gust velocity from 30 feet per second to 25 feet per second has the same effect as a 14-percent increment in stresses, if the slight change in mean-stress level is disregarded. For a 10-percent increment due to dynamic action, therefore, the single-gust life would be reduced by a factor of about 4 whereas the fatigue life would be reduced by a factor less than 2; thus the effect of dynamic response on single-gust life is more pronounced than the effect on fatigue life.

The inclusion in the analysis of stress cycles resulting from ground operation, would, on the other hand, adversely affect the fatigue life to some extent without affecting the single-gust life unless the structure were damaged in the ground operations. Both fatigue life and single-gust life may therefore be expected to be somewhat less than the values given in the analysis.

The gradual increase in the design allowable stresses for a material has not been considered in this analysis. Again, however, general conclusions may be drawn from consideration of figure 9. The change to a design gust velocity of 25 feet per second is the same as a 14-percent increase in the design allowable strength at a constant design gust velocity of 30 feet per second. A reduction of the fatigue life by one-half is associated with this change. Thus the design allowable stresses used for a material have an important effect on the fatigue life of the structure, and the trend to increased design allowable stresses and more effective utilization of a material will lead to reduced fatigue life.

It has been shown that, on the basis of the assumptions made, the fatigue life is affected by the order of stressing, and, if the first stress of a number of cycles is high, the fatigue life is appreciably increased. This result suggests that beneficial effects might be had by prestressing the fabricated structure.

COMPARISON OF FATIGUE, SINGLE-GUST, AND OPERATING LIVES

The absolute values of the fatigue and single-gust lives arrived at in this analysis may not be regarded as accurately established, as previously noted. It is of interest, nevertheless, to compare the values of life expectancy obtained in the analysis with the maximum operating lives of existing airplanes. Specific data on this subject are not available, although some information indicates that commercial transport airplanes operate regularly as much as 8 hours a day over the period of their useful lives. If a cruising speed of 170 miles per hour is assumed, an airplane flown 8 hours a day for 10 years would have an operating life of about 29,000 hours, or about 5×10^6 miles. Occasional failures of the overload type and fatigue failures with moderate values of stress-concentration factor may be expected within this life.

The fatigue life and single-gust life appear to be of about equal importance; the actual life involving either fatigue or direct failure due to overload depends on the influence of the operating conditions and the detail design and construction. A precautionary remark should be made, however, regarding any direct comparison of fatigue and single-gust lives; namely, the fatigue life applies directly to individual airplanes, whereas the single-gust life is a value of probability applicable to a considerable number of airplanes of the same type. In other words, before a fatigue failure will occur the individual airplane must be flown for some length of time but single-gust failures may occur at any time in the life of an airplane.

It should be noted that the occurrence of a fatigue failure in the primary structure does not necessarily mean catastrophic failure of the structure. Since fatigue failures occur at points of high stress concentration and may thus be localized, considerable static strength will normally remain. If the crack caused by fatigue is detected early, the defective part may be replaced and the useful life greatly prolonged. The same opportunity does not exist for correcting the effects of single excessive gusts except in the improbable case in which the stress is carried far enough beyond the elastic limit to cause noticeable permanent set but not far enough to cause complete failure while in the air.

CONCLUSIONS

In order to provide a basis for judging the relative importance of wing failure by fatigue and by single intense gusts, an analysis of wing life for normal cruising flight was made based on data on the frequency of atmospheric gusts. The independent variables considered in the analysis included stress-concentration factor, stress-load relation, wing loading, design and cruising speeds, design gust velocity, and airplane size. The results indicated that:

1. The fatigue life and single-gust life appear to be of about equal importance; the actual life involving either fatigue or direct failure due to overload depends on the influence of the operating conditions and the detail design and construction.
2. Occasional failures of the overload type and fatigue failures with moderate values of stress-concentration factor may be expected within the operating life of some existing airplanes.
3. The trends in design toward higher wing loading, reduced load factor, larger size, and increased speed appear to have a secondary effect on both the fatigue life and the single-gust life.
4. The design allowable stresses used for a given material have an important effect on the fatigue life of a structure, and the trend to increased design allowable stresses and more effective utilization of a material will lead to reduced fatigue life.
5. Fatigue life is determined primarily by detail design and construction and is affected only to a secondary degree by normal changes in operating speed and by moderate changes in design gust velocity.
6. Single-gust life is not appreciably affected by the detail design but is markedly affected by operating speed and by changes in design gust velocity.

LANGLEY MEMORIAL AERONAUTICAL LABORATORY,
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., *May 28, 1945.*

REFERENCES

1. Rhode, Richard V., and Donely, Philip: Frequency of Occurrence of Atmospheric Gusts and of Related Loads on Airplane Structures. NACA ARR No. L4I21, 1944.
2. Langer, B. F.: Fatigue Failure from Stress Cycles of Varying Amplitude. Jour. Appl. Mech., vol. 4, no. 4, Dec. 1937, pp. A-160—A-162.
3. Bland, Reginald B., and Sandorff, Paul E.: The Control of Life Expectancy in Airplane Structures. Aero. Eng. Rev., vol. 2, no. 8, Aug. 1943, pp. 7–21.
4. Gassner, E.: Festigkeitsversuche mit wiederholter Beanspruchung im Flugzeugbau. Luftwissen, Bd. 6, Nr. 2, Feb. 1939, pp. 61–64.
5. Timoshenko, S.: Strength of Materials. Part II—Advanced Theory and Problems. D. Van Nostrand Co., Inc., 1930.
6. Fox, L., and Southwell, R. V.: Relaxation Methods Applied to Engineering Problems. VIIA. Biharmonic Analysis as Applied to Flexure and Extension of Flat Elastic Plates. Phil. Trans. Roy. Soc. (London), ser. C, vol. 1, no. 2, Oct. 15, 1941, pp. 15–56.
7. Christopherson, D. G.: A Theoretical Investigation of Plastic Torsion in an I-Beam. Jour. Appl. Mech., vol. 7, no. 1, March 1940, pp. A-1—A-4.
8. Hartmann, E. C.: Fatigue Test Results. Their Use in Design Calculations. Product Engineering reprint, Feb. 1941.
9. Smith, James O.: The Effect of Range of Stress on the Fatigue Strength of Metals. Univ. of Ill. Bull. No. 334, vol. 39, no. 26, Feb. 1942.
10. Hartmann, E. C., and Stickley, G. W.: The Direct-Stress Fatigue Strength of 17S-T Aluminum Alloy throughout the Range from ½ to 500,000,000 Cycles of Stress. NACA TN No. 865, 1942.
11. Stickley, G. W.: The Fatigue Strengths of Some Wrought Aluminum Alloys. NACA RB, June 1942.